

Final Report

NASA Grant NAG 5-8618

A Study of Ion Outflow as a Source of Plasma for the Magnetosphere

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June 30, 2003

Background

Spacecraft measurements beginning in the early 1970's gave indications that the ionosphere was a contributor to the energetic particle population of the Earth's magnetosphere. This surprising result ran counter to the previously accepted model that the magnetospheric plasmas, because of their higher energies, must have come from the solar wind. Indeed, the original discovery of the Van Allen radiation belts, with energies of millions of electron volts, set a strong community belief in the sun as the plasma source because of the dramatic difference in the radiation belt energy and that of the Earth's ionospheric source.

These later measurements, made by the Retarding Ion Mass Spectrometer (RIMS) on the Dynamics Explorer satellite, showed that the possible flux of ions moving upward from the ionosphere to the magnetosphere could be substantial. The RIMS instrument was able to distinguish the mass of the upflowing ions as well as their energy and pitch angle distribution. Observations of the cleft ion fountain, the auroral ion fountain and the polar wind led to a first attempt to quantify the ionosphere outflow which was found to exceed 10^{25} ions/sec.

Given this initial set of measurements of H⁺, He⁺ and O⁺ including their energy and spatial locations in the polar regions, Chappell et al, 1987 were able to make a first set of estimates related to how these ion fluxes would move outward into the magnetosphere and populate its major regions – the plasmasphere, plasma sheet, and magnetotail lobes. These estimates utilized the best available set of low altitude ion flow measurements and combined them with an approximation of the particles' flow trajectory into the different magnetospheric regions. Given the ion flux, the volume of the regions and the estimated residence time of a particle in the region, a density could be calculated. These calculated densities matched the observed densities quite closely throughout the magnetosphere.

There were two shortcomings to the Chappell et al., 1987 study. The first was that the RIMS instrument was limited in its ability to measure the very low energy ions at high altitudes because of the positive charging of the satellite. This phenomenon is common for spacecraft at altitudes above the ionosphere which do not carry a spacecraft potential regulating device. The second limitation came from the rather crude calculation of the particle trajectories as they moved from ionosphere to magnetosphere. Both of these limitations have now been removed with the development and flight of the Thermal Ion Dynamics Experiment (TIDE) on the potential-controlled POLAR spacecraft of the Global Geospace Science mission and with the

development of a single particle magnetospheric trajectory code by Dominique Delcourt. The stage has been set to take the observations and estimates of the ionospheric source to a higher level of accuracy.

Present Situation

With the approval of the GGS mission and the proposal and acceptance of the TIDE instrument in 1978, the opportunity arose to create an instrument with a larger, more sensitive geometric factor and a smaller more accurate acceptance angle which could better characterize the low energy outflowing plasma. The higher orbit of the POLAR spacecraft compared to the Dynamics Explorer also would permit the measurement of outflowing ions high in the polar cap and at the entry interface to the lobes of the geomagnetic tail. In addition to TIDE, the Plasma Source Instrument (PSI) was also proposed and accepted for the POLAR spacecraft. It had the proven ability from previous missions to clamp the satellite potential to the surrounding plasma, hence allowing the low energy ions to be measured even at high extra-ionospheric altitudes.

The POLAR spacecraft was launched in February of 1996 into a high polar orbit with apogee over the northern polar cap of the Earth. The TIDE instrument has worked well and when the PSI is operated, the very low energy polar wind plasma can be seen moving outward at high altitudes above the polar cap and tailward toward the magnetotail lobes.

Through agreements within the POLAR science working group, the PSI/TIDE combination has been run for a period of two weeks every ten weeks. This gives a local time sampling of the ion outflow, which can permit the development of a spatial map of ion outflow. This spatial distribution, when combined with the measured flux, can be used to create a more accurate calculation of the total ionospheric outflow. In time, as the measurements are carried out in different magnetic conditions, a variable model of the ionospheric sources can be created. Using this model and the accurate trajectory/energization code of Dominique Delcourt, the populating of the magnetosphere by ionospheric plasma can be determined with an accuracy greater than ever before.

Of particular interest and importance will be the determination of the spatial extent of the ionospheric outflow. In the initial calculations of Chappell et. al., 1987, the dominant contributor of ions was thought to be the polar wind which contributed a substantial flow rate of $1-3 \times 10^8$ ions/cm²sec over a very broad area of the earth including all invariant latitudes $> 51^\circ$.

This large total outflow is critically influenced by the large area of outflow. Although the TIDE/PSI instrument combination is not operated over all latitudes and is confined more to the polar latitudes, every attempt will be made in data collection and interpretation to probe the understanding of the low latitude outflow limit and through this the total magnitude of the polar wind contribution.

Accomplishments

Under this grant, NAG5-8618, significant progress has been made in analyzing data on the magnitude of the ion outflow, its pitch angle and energy characteristics and its spatial distribution. In addition, hundreds of particle trajectories have been run using the Delcourt code. The data have been taken from a set of perigee passes in the southern hemisphere at an altitude around 5000 km.

Figure 1 shows a perigee pass of the Polar satellite showing the energy and spin angle of the upflowing ions which constitute the polar wind. These H⁺ ions have been analyzed for energy and pitch angle to determine the specific characteristics of the upflowing ions which can then be used as the input for the Delcourt particle trajectory code.

Figure 2 shows examples of the upflowing ion characteristics after the spacecraft ram and ExB drift effects have been removed. The ion energies range from < 1 eV up to 2.5 eV and their pitch angles are dominantly within 30 degrees of the upward field line direction. Statistics on energy and pitch angles are shown in Figures 3 and 4.

The upward fluxes of ions are shown in Figure 5. There is a significant variation in upward flux level, particularly with variations in the spacecraft potential as measured by the electric field experiment on the Polar spacecraft. It is clear that as the density in the topside ionosphere decreases, the charge on the Polar spacecraft increases, thereby reducing the amount of polar wind flux which can reach the TIDE instrument. Careful examination of Figure 5 shows that as the spacecraft potential approaches zero, the apparent outflow flux increases to the range of 5×10^8 ions/cm²sec. This is a very significant upward flux, which matches the predictions of

polar wind theory and the magnitude of previous measurements on Dynamics Explorer (Nagai et al, 1984). It is clear that previous satellite measurements of the polar wind such as Akebono would have been significantly affected by the spacecraft potential.

By using a large number of perigee passes, the TIDE data can be used to determine the spatial distribution and characteristics of the ion outflow. Figure 6 shows the range of pitch angle and energy for different locations across the polar latitudes extending down to 60 degrees invariant latitude. For each box in this invariant latitude, magnetic local time grid, an ion trajectory can be calculated to follow the movement and energization of the ions as they move upward into the magnetosphere.

Figures 7, 8, and 9 show three example ion trajectories. In Figure 7 the particles precipitate in the opposite hemisphere. In Figure 8, the particles bounce and drift around the Earth attaining energies of 10's of eV. In Figure 9 the particles are convected back into the tail of the magnetosphere where they are energized to plasma sheet energies and subsequently to ring current energies as they drift back into the inner magnetosphere. It is clear from these example trajectories that the ionospheric supply can furnish ions to various regions of the magnetosphere with the characteristic energies that have been observed by a multitude of previous spacecraft such as OGO, ISEE and AMPTE.

The next step, then, has been to follow the trajectories of ions from all of the different spatial locations in the outflow grid. Figure 10 shows one example of outflow for the low energy and minimum pitch angle limits of the outflowing ion characteristics. The letters in the boxes show the resulting trajectories of the particles including precipitation, bouncing, loss to magnetosheath, forming plasma sheet and forming ring current. This figure, then, gives an indication of the areas of the topside ionosphere that can supply particles to the plasma sheet and ring current.

The preceding figures display the exciting results that have been achieved through the support of this grant. This work has been done as part of the Ph.D. thesis of Matthew Huddleston who is in the process of completing his degree at Vanderbilt. The work that will be proposed in a follow-

on study will complete the determination of the magnetospheric densities and energies in different key regions that are supplied by the ionospheric outflow.

A goal of the initial work has been to complete a set of papers that have been presented at a series of AGU meetings. A review paper on the strength of the ionospheric source was published in the *Journal of Atmospheric and Solar-Terrestrial Physics*, (Chappell et al., 2000). A paper for the *Journal of Geophysical Research* is in process. References for the papers and presentations are given in the bibliography below. Vanderbilt University has been quite honored to have the opportunity to work with the National Aeronautics and Space Administration on this important research initiative.

References:

Chappell, C.R., T.E. Moore, and J. H. Waite, Jr., "The Ionosphere as a Fully Adequate Source of Plasma for the Earth's Magnetosphere," *Journal of Geophysical Research*, 5896, 1987.

Nagai, T., J.H. Waite, Jr., J.L. Green, C.R. Chappell, R.C. Olsen, and R.H. Comfort, "First Measurements of Supersonic Polar Wind in the Polar Magnetosphere," *Geophys. Res. Lett.*, 11(7), 669, 1984).

Chappell, C.R., B.L. Giles, T.E. Moore, D.C. Delcourt, P.D. Craven, M.O. Chandler, "The Adequacy of the Ionospheric Source in Supplying Magnetospheric Plasma," *Journal of Atmospheric and Solar-Terrestrial Physics*, 62, 421, (2000).

Chappell, C.R., M.M. Huddleston, T.E. Moore, B.L. Giles, and M.O. Chandler, "Low Energy Ion Interchange Between the Ionosphere and Plasma Sheet," *EOS, Transactions of the American Geophysical Union*, Spring, 2002.

POLAR TIDE/PSI

start time: 04/09/96 06:02:27 UT

stop time: 04/09/96 06:28:02 UT

no spin averaging

collapse option 4

ranges used for sum:

energy (RPA V): 0.00-300.00

spin angle: 0.00-360.00°

polar channels: 1-7

Energy Flux

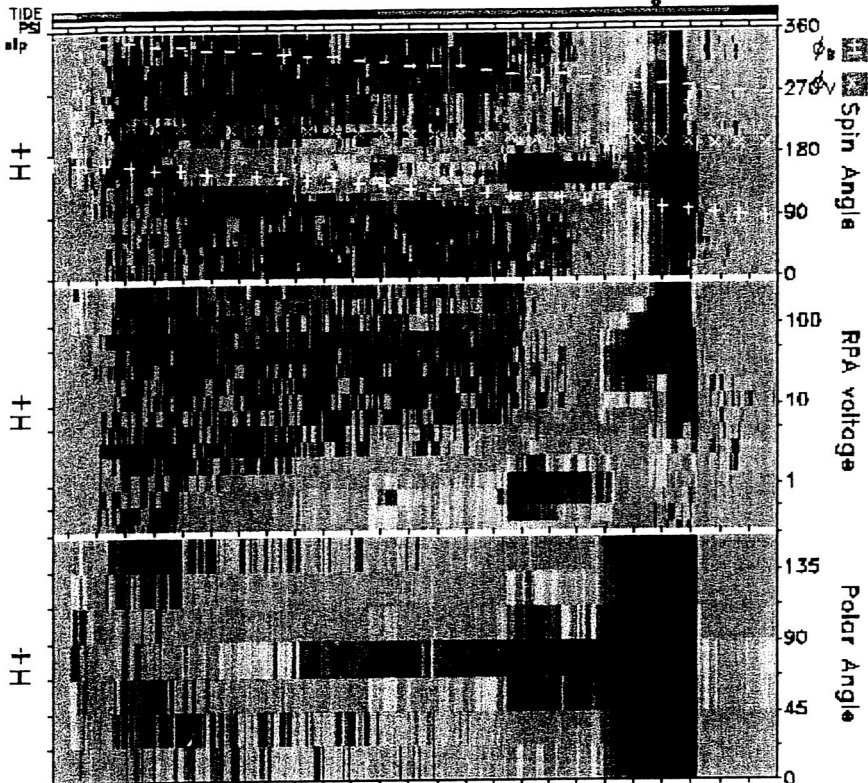
[
log
[V₀, V₁, V₂, V₃, V₄, V₅, V₆, V₇]
]no data
no cnts

standby

sp TIDE

off PSI

mir slip



time	06:05	06:10	06:15	06:20	06:25	hr:min
Re	1.8	1.9	1.8	1.8	1.8	Re
Lshell	10.6	23.7	76.5	49.9	15.2	
mlt	1.7	2.5	4.9	9.4	11.0	hrs
mlat	-64.3	-73.5	-81.0	-78.9	-69.7	deg
inlat	72.1	78.1	83.4	81.9	75.1	deg

sector_sens: sector_sens.v3
 tide_x.y4.1.0
 calibration: tide_calib.v5
 mode_calibration: mode_calib.v7
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 level-zero: 96040901.dat

Figure 1

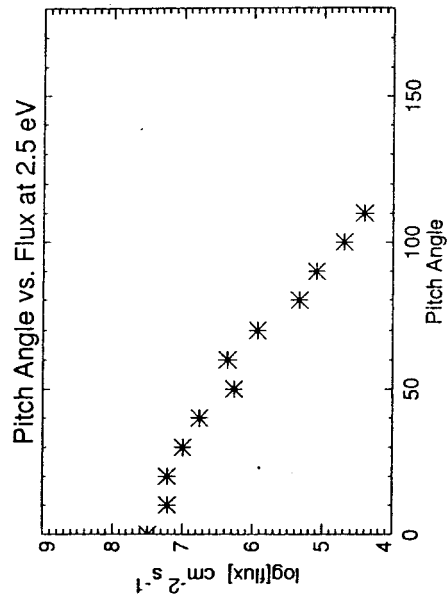
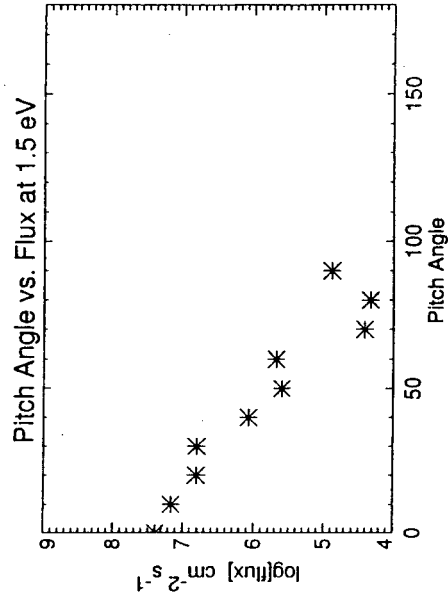
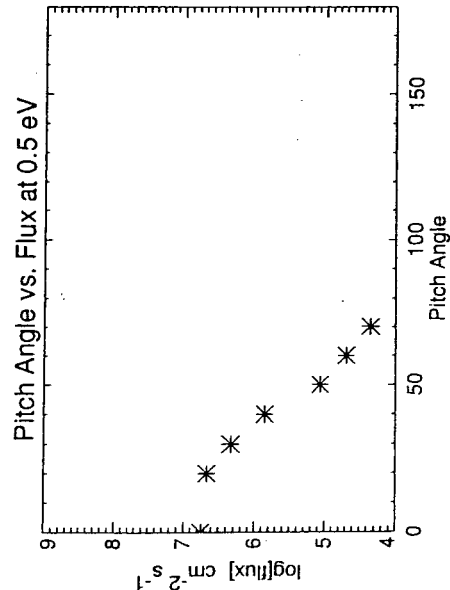
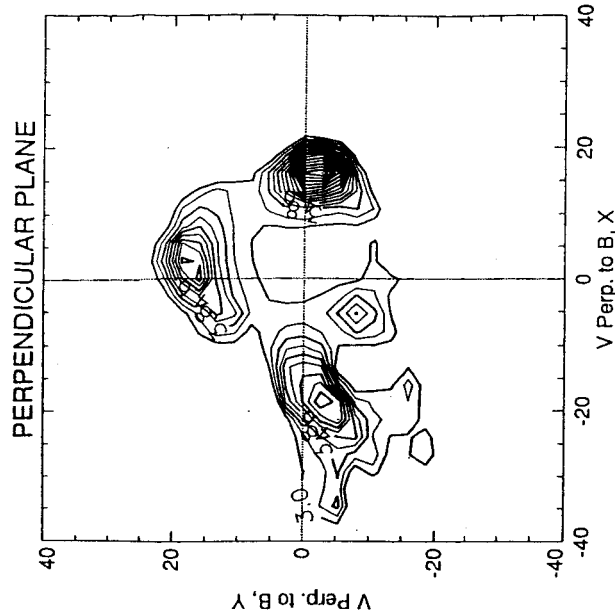
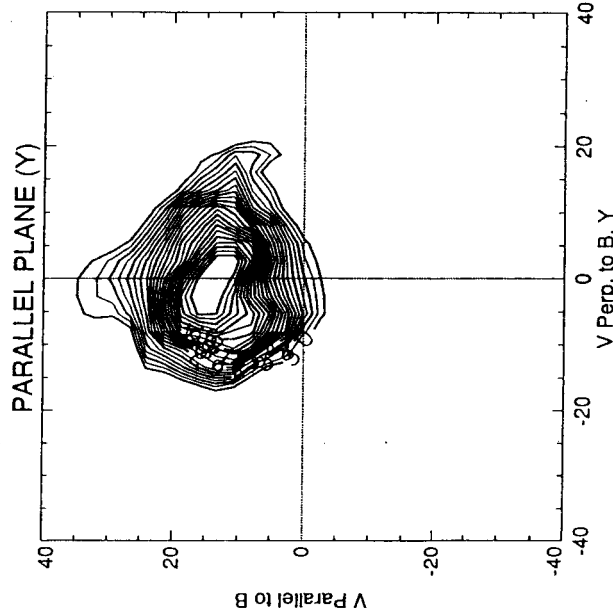
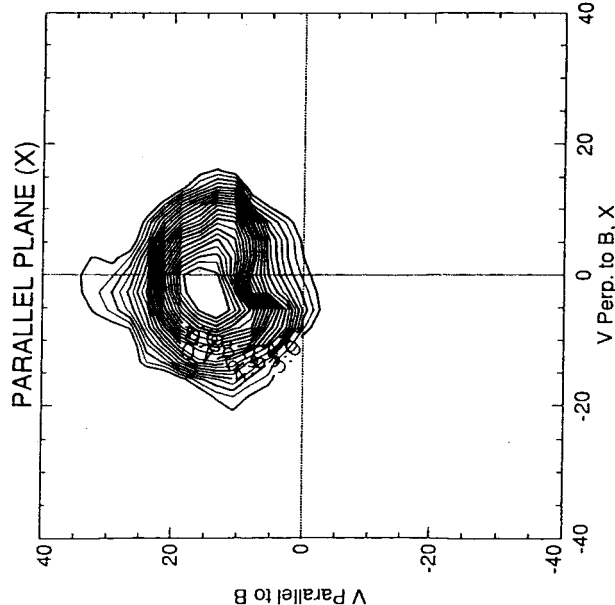
Cross Sections of TIDE Distribution H+

960420 Start: 05:15:00 Stop: 05:16:59 UT

Dipole B(nT): -4797.4-17101.7 2496.3 17936.4 Re: 1.88 MLT: 1.97 MagLat: -75.99

Coord. Sys. Vsc (km/s) Vdrift (km/s) Vtot (km/s)

S/C 7.4 -0.5 -0.1 -2.7 -0.2 -6.5 4.7 -0.7 -6.6



Slice extent: +/-90.0 deg

Figure 2

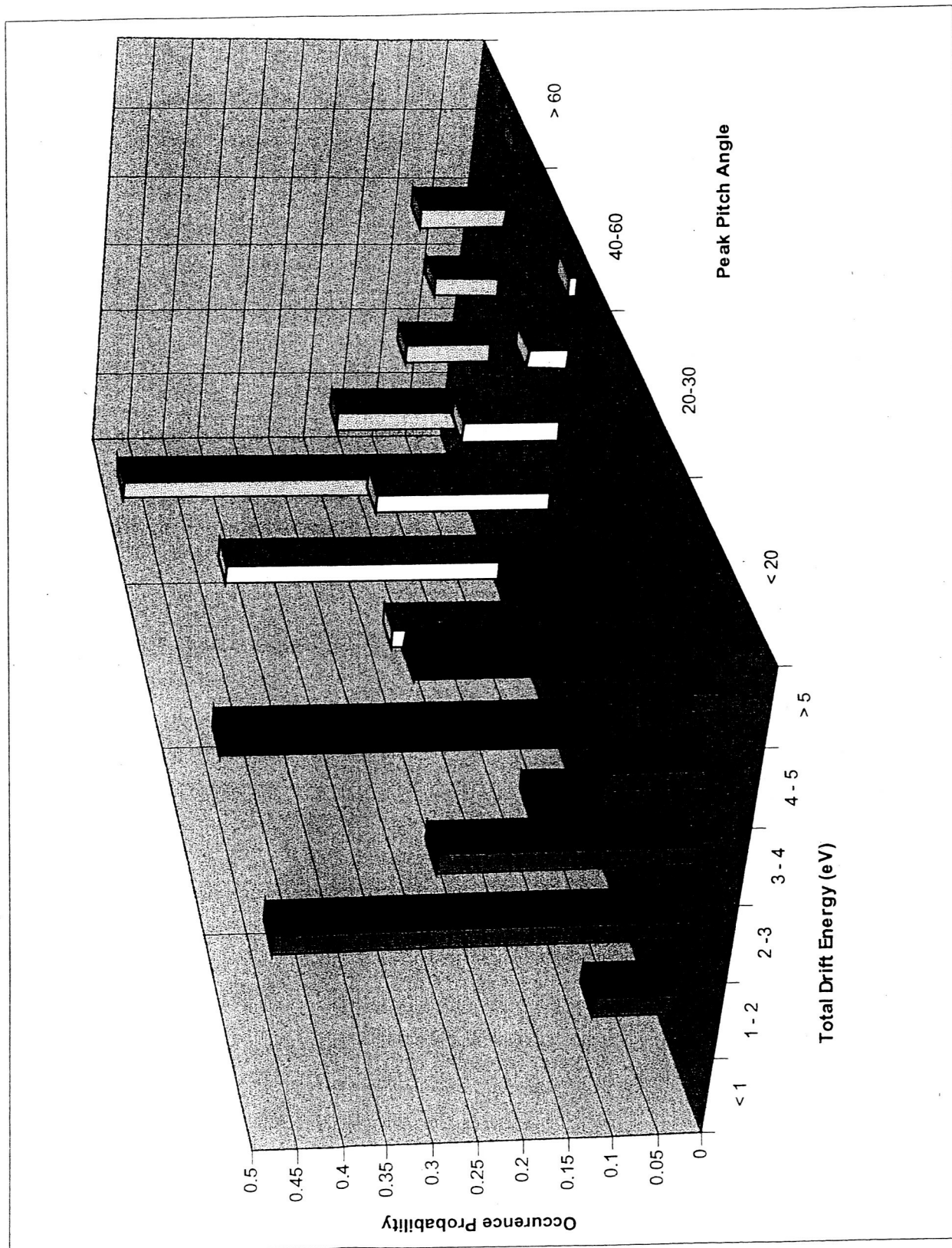
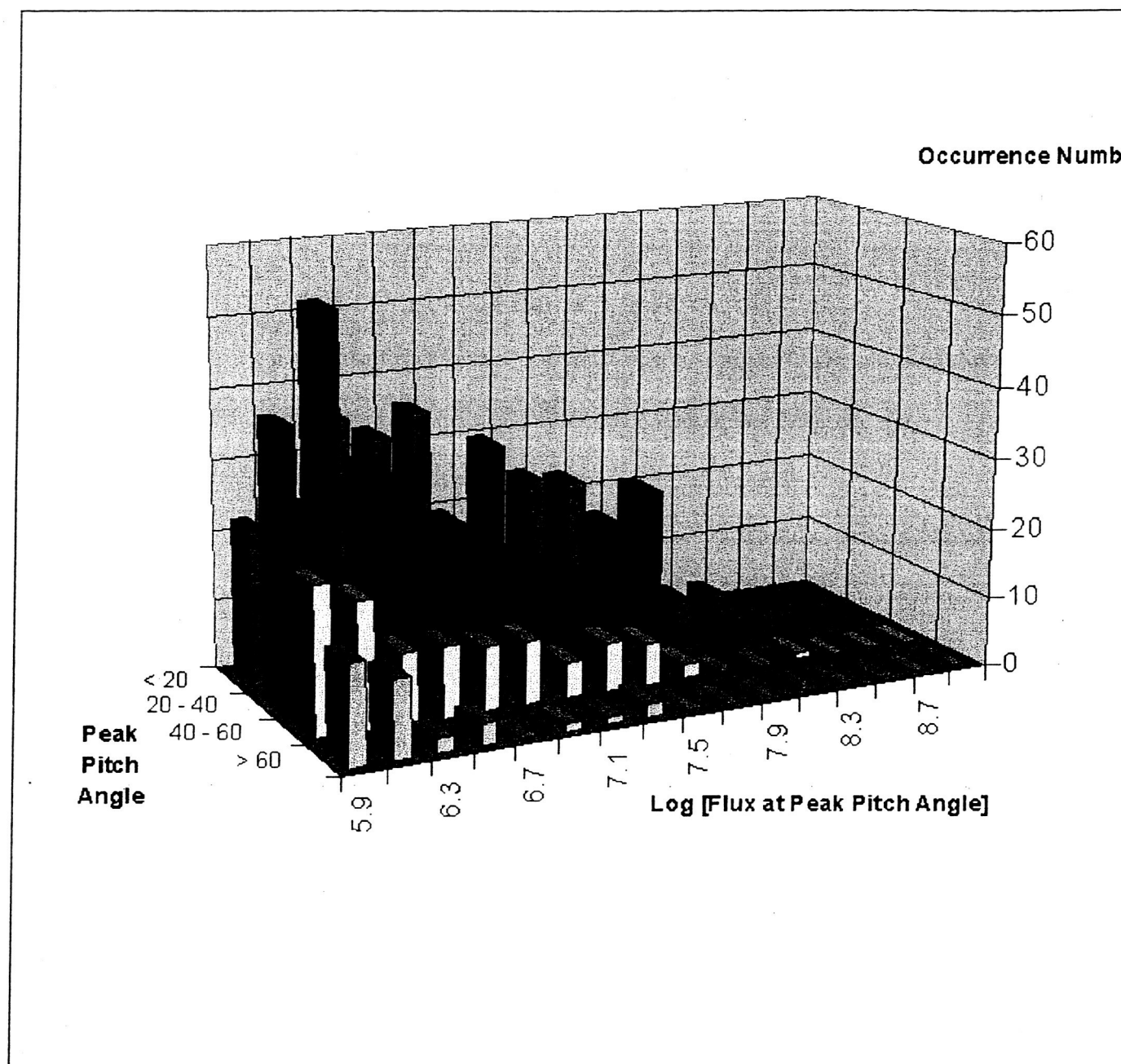


Figure 3

*Figure 4*

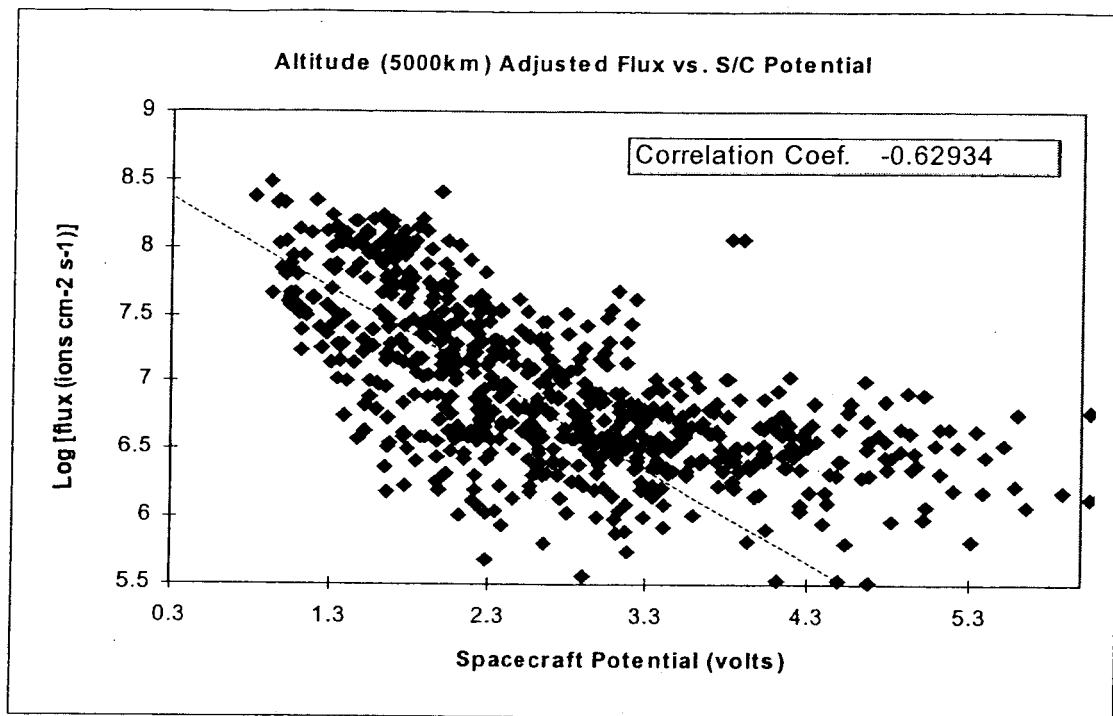
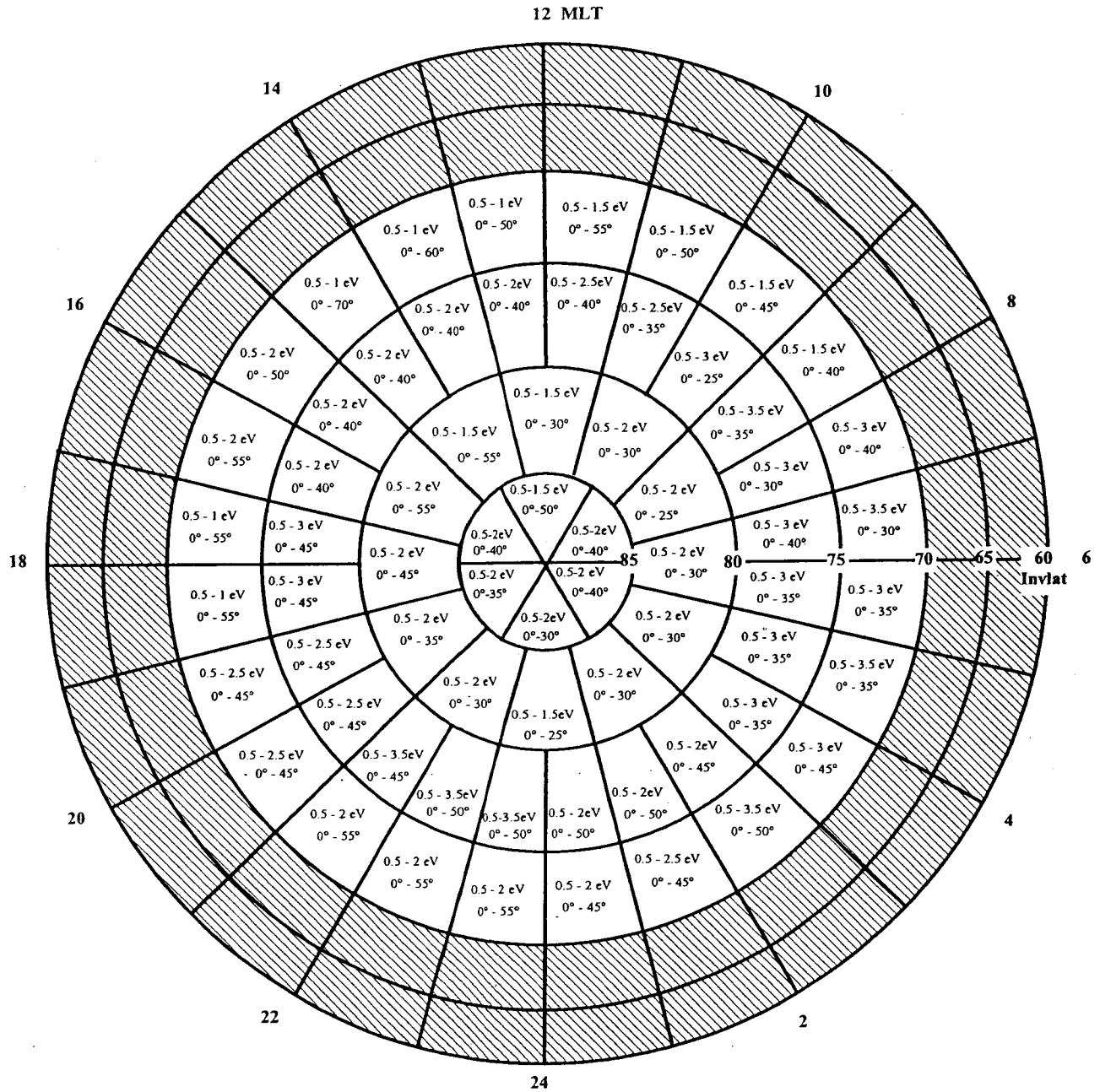


Figure 5



Polar Wind Input Grid: Energy and Pitch Angle Range Verses Location

Source altitude is 5000 km.

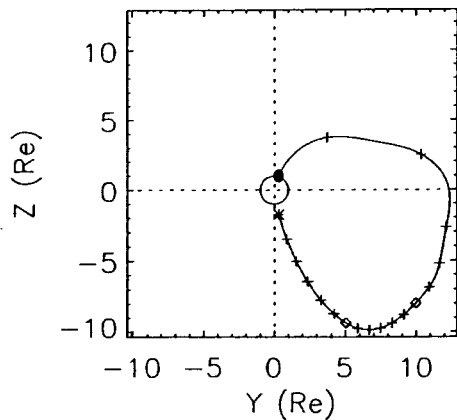
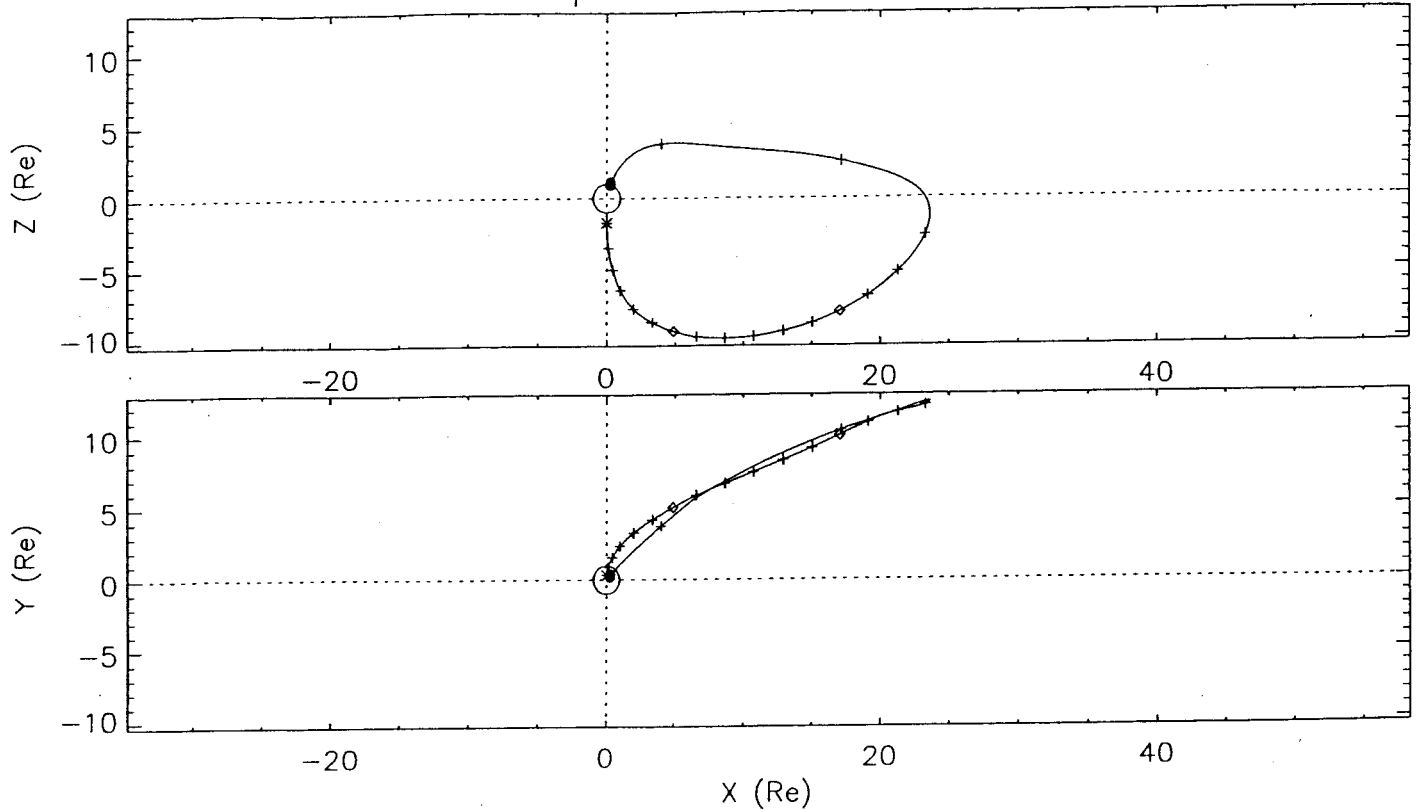
Source fluxes are $1 - 4 \times 10^8$ ions $\text{cm}^{-2} \text{s}^{-1}$ for each grid point.



Area not included in TIDE survey.
Values extrapolated from survey data.

Figure 6

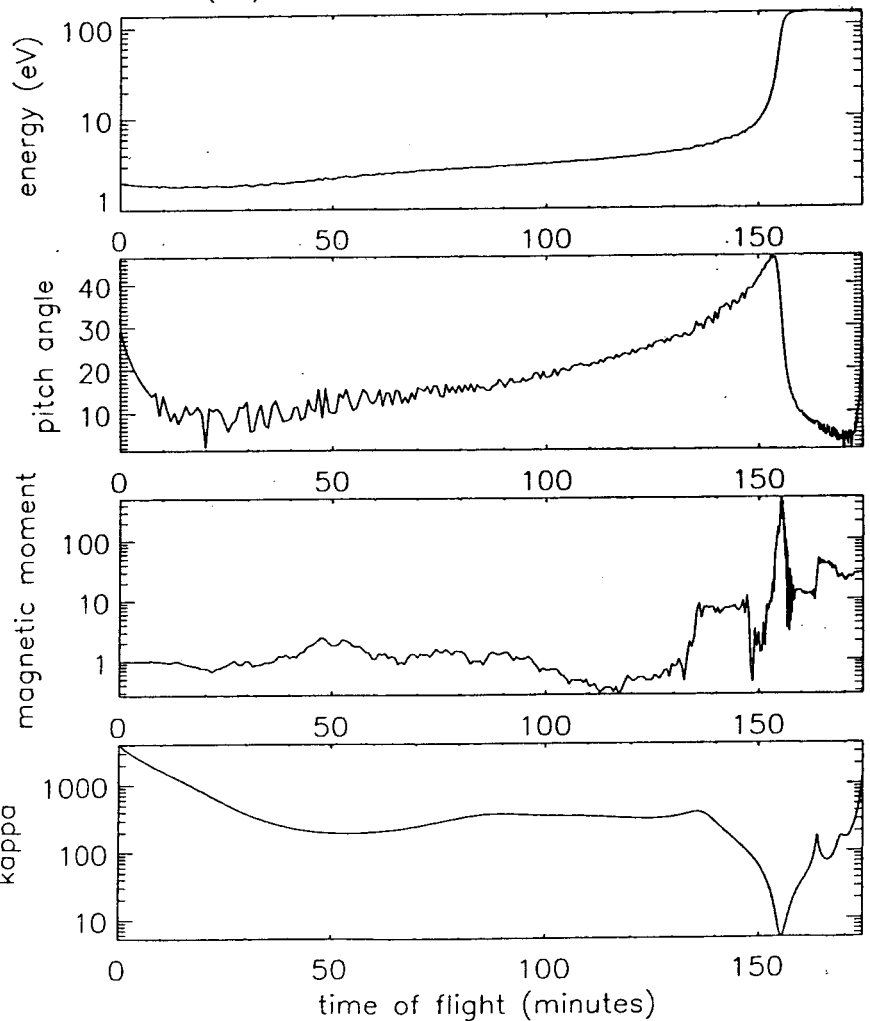
Test-particle code of D. Delcourt



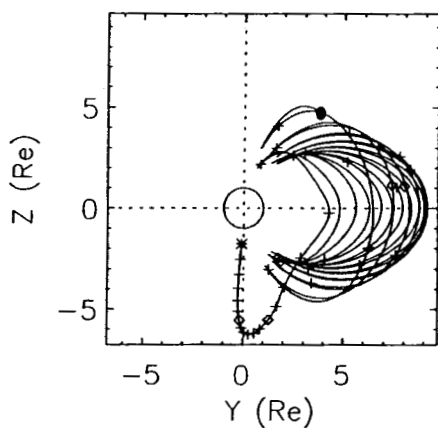
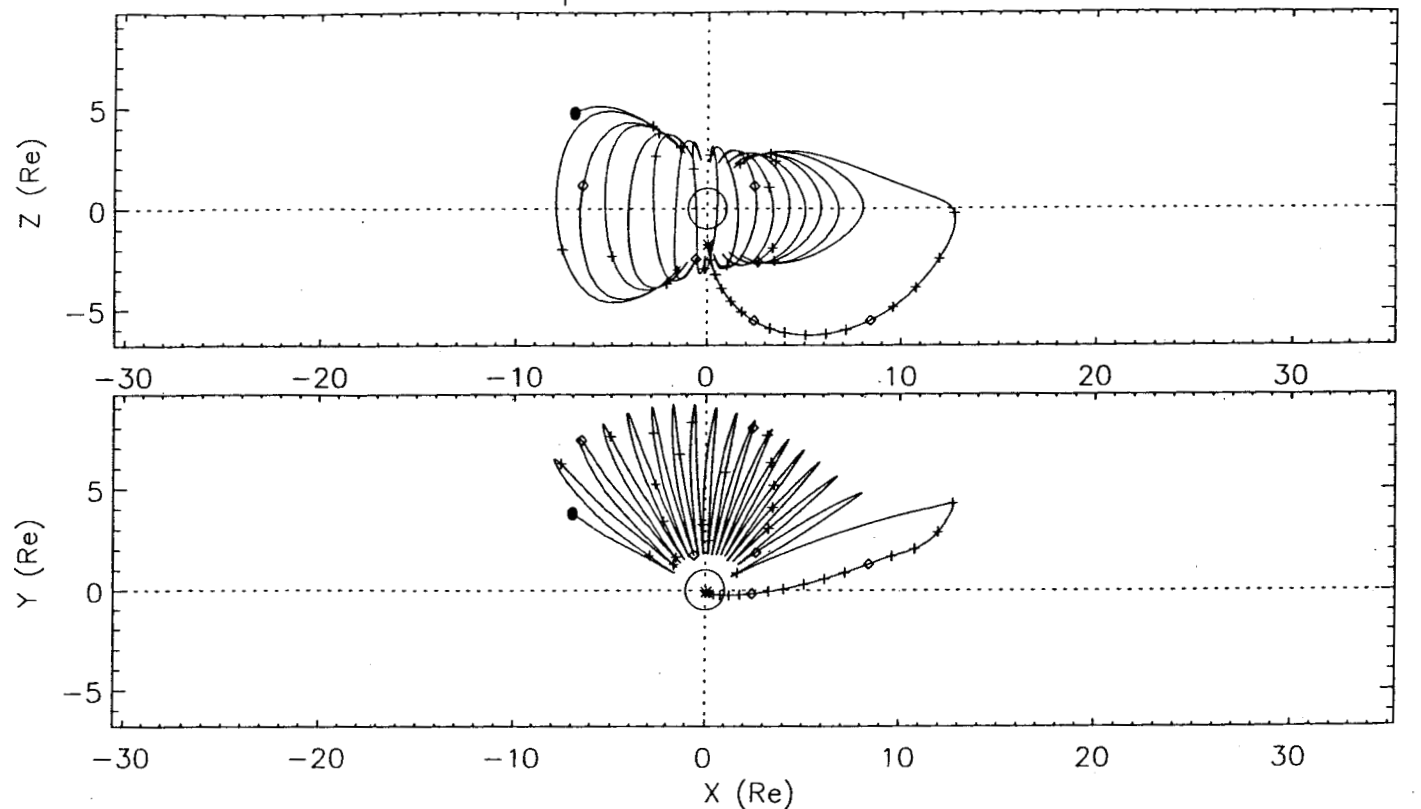
Start, Stop Parameters:

Time (minute): 0.000, 174.000
Local time: 6.000, 3.204
Latitude: -80.000, 69.350
Distance (Re): 1.78, 1.10
Energy (eV): 2.00, 130.20
Pitch angle: 30.000, 40.350
Phase angle: 0.00, 267.10

file: ./temp/quietwin9D.dat



Test-particle code of D. Delcourt



Start, Stop Parameters:

Time (minute): 0.000,400.000
 Local time: 20.000, 10.100
 Latitude: -86.600, 30.820
 Distance (Re): 1.78, 9.24
 Energy (eV): 0.50, 82.42
 Pitch angle: 35.000, 169.300
 Phase angle: 0.00, 323.70

file: ./temp/quietwin20F.dot

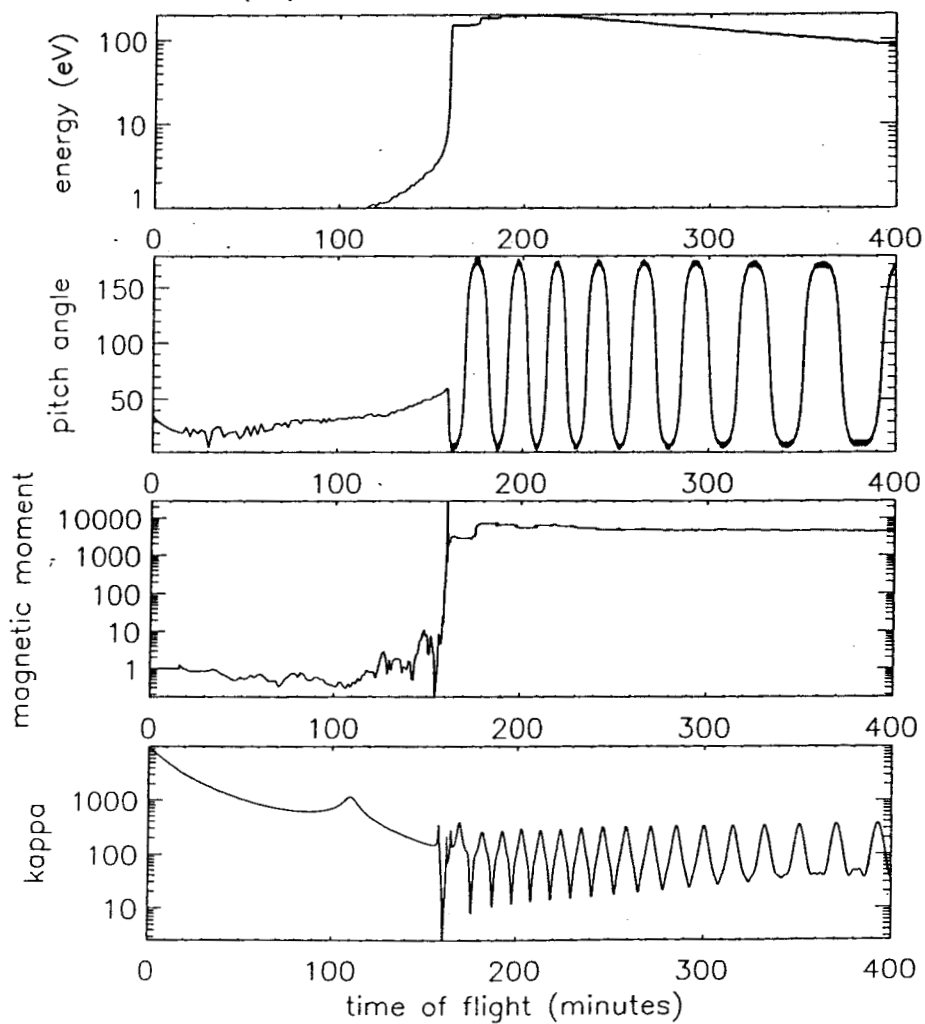
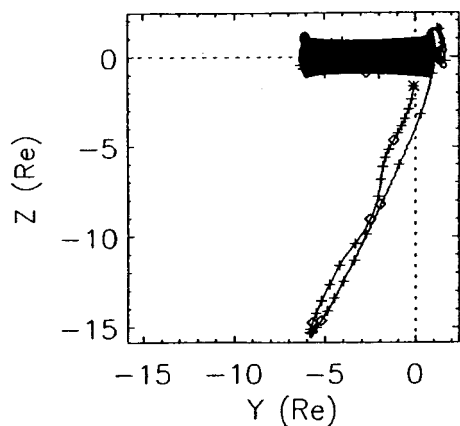
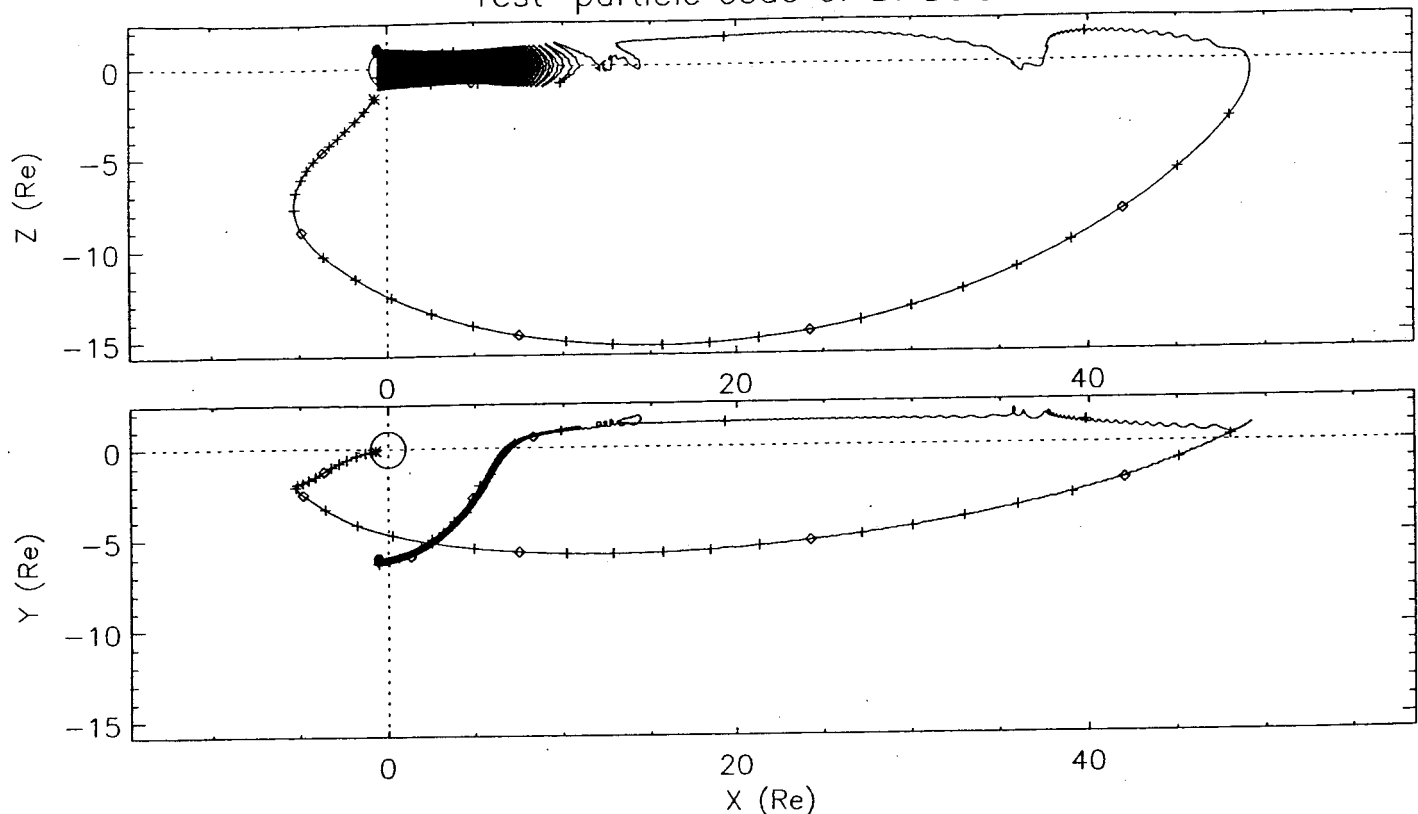


Figure 8

Test-particle code of D. Delcourt



Start, Stop Parameters:

Time (minute): 0.000,510.167
 Local time: 12.500, 17.660
 Latitude: -66.300, 9.493
 Distance (Re): 1.78, 6.20
 Energy (eV): 0.50, 11360.00
 Pitch angle: 0.100, 77.490
 Phase angle: 0.00, 102.50

file: trace/auto2Mshort.dat

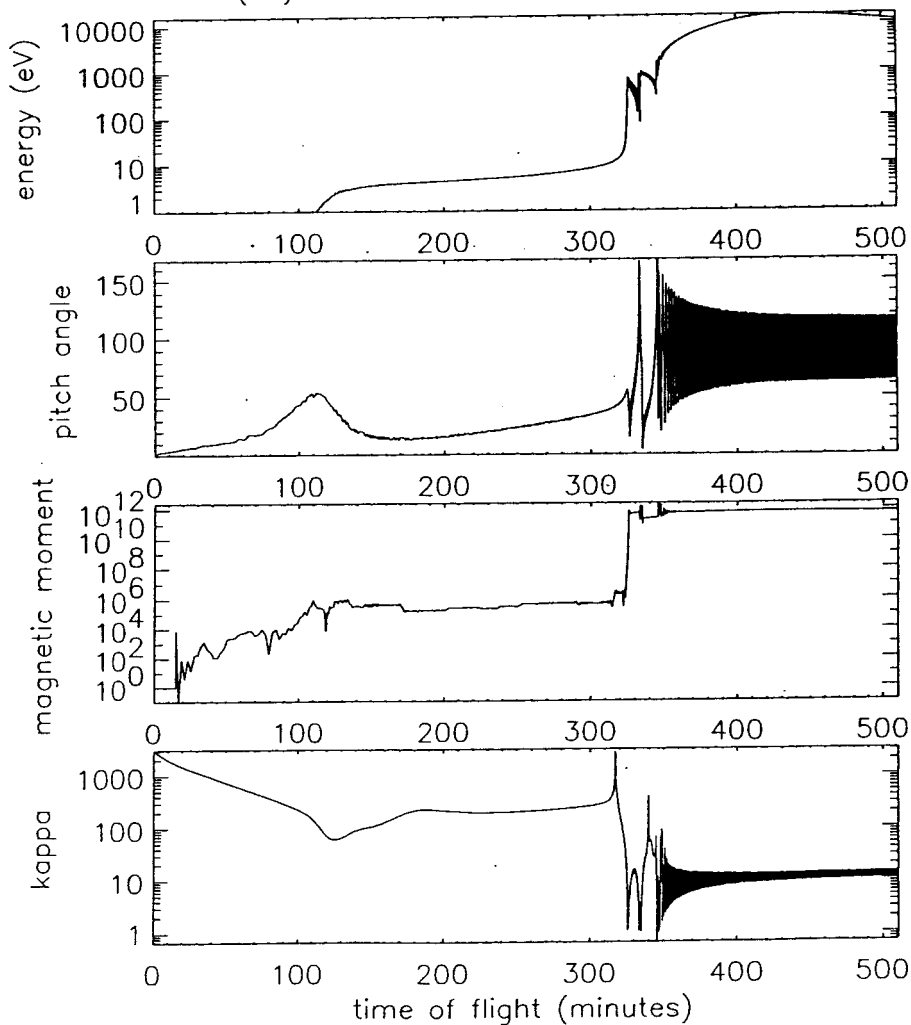
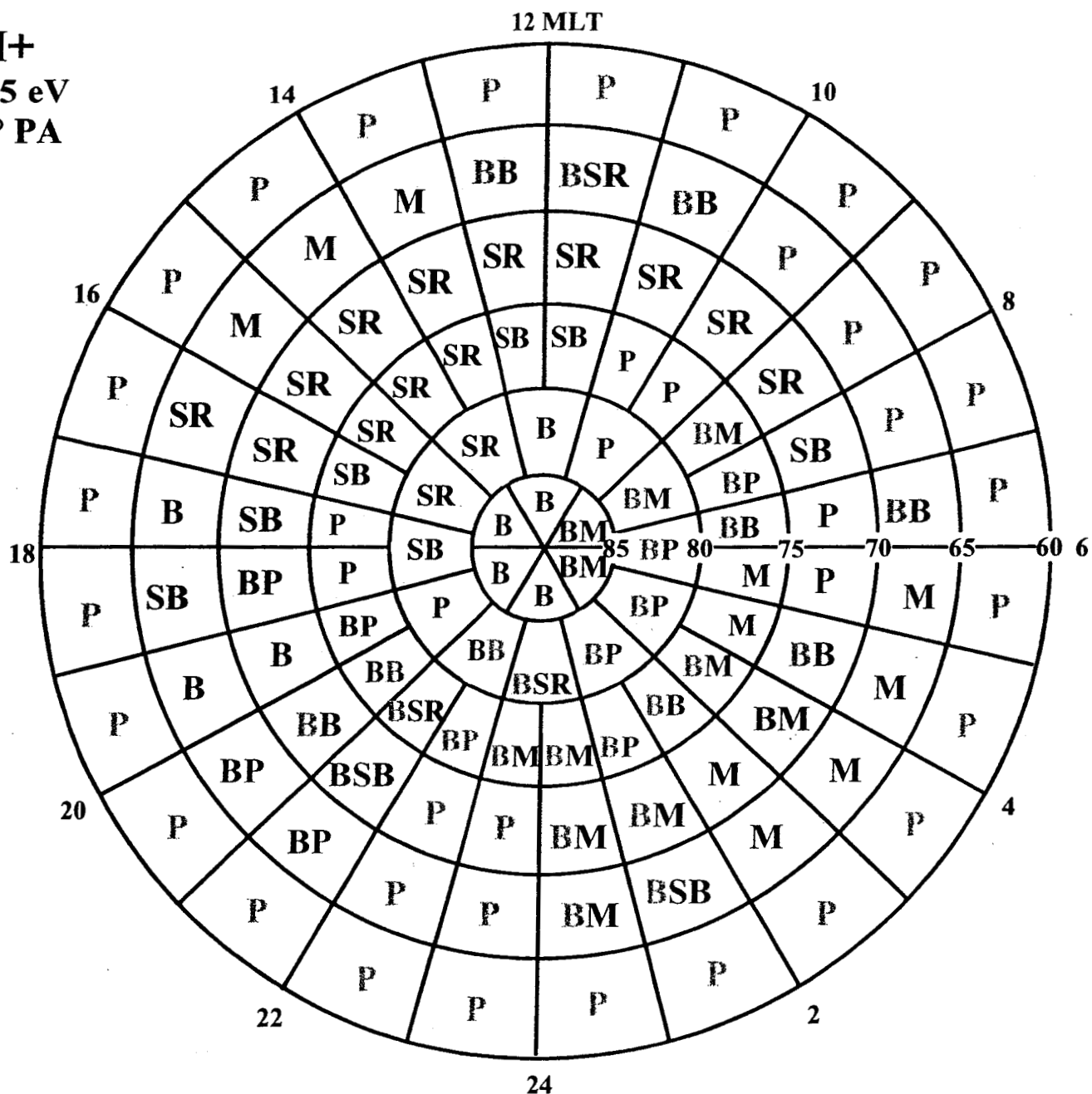


Figure 9

H+
0.5 eV
0° PA



Energy

< 10 eV

10 – 500 eV

0.5 – 3 keV

> 3 keV

P -- ions precipitate in conjugate ionosphere

B -- ions reflect (bounce) between hemispheres

M -- ions escape into the magnetosheath

S -- ions form plasma sheet

R -- ions form ring current

Figure 10